# Numerical and Experimental Analysis of Diesel Spray Dynamics including the Effects of Fuel Viscosity


By

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**Dedication**

To my parents Bong Chee Kong and Tay Ah Tet,

my sisters San Mei Bong and Siew Mai Bong

and my love, Yun Chen.

**Figure of a numerical predicted diesel spray computed using Star-CD v3.26 and plot generated using Matlab v7.5.**

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# Abstract

The maritime transport industry carries the majority of global trade. Large ships use diesel engines that are significantly larger than automotive diesel engines and consume low quality heavy fuel oil (HFO). This project aimed to better understand the dynamics of long duration, high fuel viscosity diesel sprays that are typical of a marine engine and to improve the accuracy of CFD models used for optimisation of engine design. The project utilised both numerical methods and experimental methods. The numerical software package called "Star-CD v3.26" was used for the numerical simulation part of the project. For the gas phase, the Large Eddy Simulation turbulence model was employed throughout. New sub-models were added to the Star-CD software to improve the simulation accuracy. Experiments were conducted using a custom-built High Pressure Spray Chamber (HPSC). The experimental results provided verification of the simulation results.

Literature reviews showed that limited research has been done on long duration HFO sprays. Most literature is focused on high speed diesel sprays with short injection durations using low viscosity fuel with light components. The low fuel viscosity has negligible effect on the droplet breakup process and numerical modelling requires only a single component fuel. Such studies can not be applied in HFO due to the high viscosity, complex molecular structure, presence of liquid phase soot, and variable fuel density. As a result, this project aimed to perform a thorough study of the fundamental dynamics of such sprays.

Throughout this project, the spray was studied at the gas density equivalent to combustion chamber density of approximately 35 $kg/m^3$ and at room temperature. This allowed the dynamics of the spray to be studied in the absence of combustion and evaporation. In the case of the HFO combustion spray, the presence of high molecular weight components and the formation of carbonaceous residue means that the spray remains as a multiphase flow throughout the combustion period.

The first phase of the project involved evaluating Lagrangian-Eulerian multiphase numerical models. In each evaluation, the models were isolated so that only the effects from the model of interest were shown in the results without unwanted influence of other models. The evaluation found that the inter-droplet collision model required corrections which resulted in the development of the mesh independent O'Rourke collision model (MIOC). The collision model studies showed that the nozzle exit region and the initial droplet cluster region contained the highest collision rate. This was because the droplet population was dense and the droplet

velocities were high in these regions. The Kelvin-Helmholtz/Rayleigh-Taylor (KH-RT) hybrid breakup model and Taylor Analogy Breakup (TAB) based dynamic droplet drag model were programmed into Star-CD v3.26.

The second phase of the project involved conducting experimental analysis of the spray. The experiment was broken into three parts, namely: spray penetration and cone angle, light sheet Particle Image Velocimetry (PIV) and dropsize shadowgraphy using a long-distance microscope. The macro spray structure (penetration experiments) and PIV experiments showed evidence that surface instabilities from the shearing of the jet against the surrounding gas, and the in-flow of air into the low pressure region of the spray jet, forms the overall spray structure. The experiment confirmed that increasing gas density results in a lower penetration rate and larger cone angle. The increase of fuel viscosity had a negligible effect on the spray penetration but increased the cone angle. PIV measurements were performed on the spray droplets because it was difficult to externally introduce seeding particles. As a result, it was not possible to adjust the seeding particle population density directly. The measured droplet velocities can be considered equivalent to the gas velocities in the sparse region of the spray because the numerical results suggested that there is minimal difference between the gas and droplet velocity. The spray images and the macro-PIV analysis showed the presence of high velocity regions and the presence of droplet clusters. The dropsize shadowgraphy experiments provided point velocity measurements that could be analysed using Particle Tracking Velocimetry (PTV) and μ-PIV methods. The results were compared with the macro-PIV results. The dropsize shadowgraphy results provided valuable dropsize data and confirmed that high fuel viscosity had a significant effect on the dropsize of the spray.

The third phase of the project involved the full numerical simulation of the diesel spray and validation with the HPSC experimental results. The validation confirmed that the KH-RT breakup model was able to reasonably predict the effects of fuel viscosity on dropsize, which was not the case with the Reitz-Diwakar breakup model. The penetration and cone angle validation showed very similar penetration rates in both numerical and experimental results, but the cone angle of the numerical simulation was narrower compared to the experimental results. The PIV measurements and simulation velocity profiles showed similar velocity patterns and velocity magnitudes at the sparse region of the spray. In the dense region, the velocity patterns remained similar but the magnitude of the predicted spray velocity was higher. This was because the experimental results were erroneous in the dense region, due to higher particle density leading to multiple scattering. The dropsize validation showed that the numerically predicted dropsize was slightly larger than the experimental results but consistent under all conditions. It was concluded that the set-up using Large Eddy Simulation (LES) with Blob atomisation, KH-RT breakup model, MIOC model, TAB based droplet drag model and vertex based interpolation, produced the most accurate simulation when validated against the experimental results.

The full spray simulation suggested that the spray structure could be divided into two regions. The disintegration region showed that most of the breakup process and momentum transfer (from droplets to gas) occurred here. The stable region showed the formation of droplet clusters and volumetric expansion of the spray. The numerical simulation results showed that a high viscosity fuel spray contained significantly different internal structures compared to a low viscosity fuel spray. This was also partly supported by the experimental results. The high viscosity fuel spray droplet dispersion rate was significantly lower and the formation of droplet clusters occurred much further away from the nozzle, when compared to low viscosity fuel spray. The results also showed that an increase in gas density shortened the length between cluster formations.

The outcome of this project is improved understanding of long duration, high fuel viscosity diesel sprays. It is concluded that the use of LES as the turbulence model produces good qualitative internal spray structures that predict the instantaneous turbulent jet instability and the formation of droplet clustering. The project highlights the limitations in the current state of numerical prediction methods and recommendations are made for future work to improve numerical predictions.

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# Nomenclature

| Symbol | Description | Units |
|---|---|---|
| $A_{noz}$ | Injection nozzle area | $mm^2$ |
| $b$ | Impact parameter used in the study of inter-droplet collision | |
| $C_D$ | Drag coefficient (of the droplet) | |
| $C_d$ | Discharge coefficient of the injector nozzle | |
| $D$ | Current droplet diameter | µm |
| $D_0$ | Initial droplet diameter | µm |
| $D_{d1}$ | Droplet diameter of the first selected droplet | µm |
| $D_{d2}$ | Droplet diameter of the second selected droplet | µm |
| $D_{dif}$ | Diffraction limit of the microscope. $D_{dif} = 1.22 \cdot \Lambda \cdot f_{\#}$ | µm |
| $D_{P1}$ | Arbitrary diameter of the first selected parcel | µm |
| $D_{P2}$ | Arbitrary diameter of the second selected parcel | µm |
| $D_s$ | Stable droplet diameter | µm |
| $D_{noz}$ | Nozzle diameter | mm |
| $E_{.95}$ | Standard error at 95% confidence interval $E_{.95} = 1.96 \cdot \frac{s}{\sqrt{N}}$ | |
| $e_{.95}$ | Percentage of the standard error $e_{.95} = \frac{E_{.95}}{\bar{x}} \cdot 100\%$ | % |
| $E_n$ | Normalised error i.e. standard error divided by mean | |
| $E_{xz}$ | $u_x$ rate of change along z-axis direction $E_{xz} = du_x/dz$ | $s^{-1}$ |
| $E_{zx}$ | $u_z$ rate of change along x-axis direction $E_{zx} = du_z/dx$ | $s^{-1}$ |

| | | |
|---|---|---|
| $f_{\#}$ | Focus number (camera lens specific term). $f_{\#} = x/D$ | |
| $I_i$ | Turbulent intensity $I_i = \frac{s_i}{\overline{u}_i}$ | |
| $L_c$ | Liquid core length | mm |
| $m$ | Mass of the droplet | kg |
| $N$ | Droplet population in a given parcel or number of image sample | |
| $P_i$ | Injection pressure | MPa |
| $P_a$ | Ambient pressure | MPa |
| $p$ | Probability | |
| $R_{xz}$ | Reynolds stress about x-axis. $R_{xz} = \frac{\sum\left[\left(u_x - \overline{u}_x\right)\left(u_z - \overline{u}_z\right)\right]}{N}$ | $m^2s^{-2}$ |
| $r$ | Radius of the droplet | µm |
| $s_N$ | Normalised RMS $s_N = \frac{s}{\overline{x}} \times 100\%$ | |
| $T$ | Temperature | °C |
| $t_0$ | Start of injection | |
| $t_1$ | Time of first experiment recording measured from $t_0$ | ms |
| $t_2$ | Time of second experiment recording measured from $t_0$ | ms |
| $t_{12}$ | Time duration between the first and second recording | µs |
| $t_3$ | Time at the end of injection measured from $t_0$ | ms |
| $u$ | Velocity (of the droplet or gas) | m/s |
| $u_{rel}$ | Relative velocity between droplet and gas | m/s |
| $V$ | Volume | $m^3$ |
| $x$ | Sample value or distance | |
| $\overline{x}$ | Sample mean | |

| | | |
|---|---|---|
| $\Delta$ | Ratio between two droplets (or difference of the two items) | |
| $\Lambda$ | Wavelength of the light | nm |
| $\Lambda_{KH}$ | KH instability wavelength | |
| $\Lambda_{RT}$ | RT instability wavelength | |
| $\Omega_{KH}$ | KH instability growth rate | |
| $\Omega_{RT}$ | KH instability growth rate | |
| $\phi$ | Fractional volume of liquid in a given volume of gas | |
| $\mu$ | Dynamic viscosity | kg/(ms) |
| $\rho$ | Density of the fluid | kg/m$^3$ |
| $\sigma$ | Surface tension (between liquid fuel and air) | N/m |
| $\tau_b$ | Breakup timescale | µs |
| $\omega_y$ | Rate of rotation about y (out of plane vorticity). $\omega_y = E_{zx} - E_{xz}$ | s$^{-1}$ |

Subscript

| | |
|---|---|
| *0* | Initial condition |
| *1* | First experimental recording of the current spray event |
| *2* | Second experimental recoding of the current spray event |
| *3* | End of injection |
| *a* | Gas (air) phase |
| *inj* | Parameter from injection of the spray |
| *l* | Liquid (Fuel) phase |
| *rel* | Relative value |
| *s* | Stable condition |

Abbreviations

| | |
|---|---|
| CAB | Cascade Atomisation Breakup model |
| CDF | Cumulative Distribution Function |
| CFD | Computational Fluid Dynamics |
| DOF | Depth of Field |
| ETAB | Enhanced Taylor Analogy Breakup model |
| FV | Fractional Volume ( $\phi$ ) |
| GS | Grid-Scale length (used in LES) |
| HFO | Heavy Fuel Oil |
| HPSC | High Pressure Spray Chamber |
| KH | Kelvin-Helmholtz (referring to the Kelvin-Helmholtz instability) |
| KH-RT | Kelvin-Helmholtz Rayleigh-Taylor Hybrid breakup model |
| LES | Large Eddy Simulation turbulence modelling technique |
| LIF | Laser Induced Fluorescence |
| MIOC | Mesh Independent O'Rourke Collision model |
| ND | Neutral Density (camera filter) |
| NS | Navier-Stokes equation |
| Oh | Ohnesorge number $Oh = \mu_l \big/ \sqrt{\rho_l \cdot \sigma \cdot D}$ |
| PDF | Probability Density Function |
| PDPA | Phase Doppler Particle Analyser |
| PIV | Particle Image Velocimetry |
| PTV | Particle Tracking Velocimetry |
| RANS | Reynolds-Average Navier-Stokes turbulence modelling technique |
| Re | Reynolds number $\mathrm{Re} = \rho_a \cdot u_{rel} \cdot D / \mu$ |

| | |
|---|---|
| RMS | Root mean square or standard deviation of the sample (N) |
| | $RMS = \left( \frac{1}{N-1} \sum_{i=1}^{N} \left( x_i - \overline{x} \right)^2 \right)^{0.5}$ |
| RNG | Renormalisation Group, a version of the *k*-*ε* turbulence model |
| RT | Rayleigh-Taylor (referring to the Rayleigh-Taylor instability) |
| SGS | Sub-Grid-Scale length (used in LES) |
| SMD | Sauter Mean Diameter ( $D_{32}$ ) |
| TAB | Taylor Analogy Breakup model |
| TDC | Top Dead Centre |
| VCO | Valve Covered Orifice (a type of injector nozzle design) |
| We | Weber number $We = \rho_a \cdot D \cdot u_{rel}^2 / \sigma$ |